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GEOLOGIC SETTING AND LITHOLOGIC COLUMN OF THE CAJON PASS DEEP DRILLHOLE

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Abstract. The Cajon Pass Deep Drillhole penetrates a late Tertiary basin developed on crystalline basement in the SW Mojave Desert, 4 km from the San Andreas fault. Cores, continuous cuttings and geophysical logs from phase I show great diversity in rock types, structure, and alteration. The hole encountered Cajon formation arkoses; granodiorite/tonalite; unusual megacrystic granite and augen gneiss; granitic and pelitic gneisses with quartzite; quartzofeldspathic orthogneiss cut by sheets of hornblende gabbro; and interlayered mafic and quartzofeldspathic orthogneisses with rare calcsilicate intervals. Foliation and compositional layering have low dips throughout the column and layered gneisses contain 10-cm-scale recumbent folds. Faults and alteration zones bound several rock units with low apparent dips. Basement cores are typically cut by steep fractures, <1 mm wide, that contain zeolites$\pm$calcite or chlorite-epidote. Fractures and faults decrease in abundance with depth.

Introduction

The Cajon Pass Deep Drillhole (CPDDH) is located 32 km (20 miles) N of San Bernardino, California, in the Cajon 7.5' quadrangle, at 999 m above m.s.l. The San Andreas fault (SAF) is located 4 km (2.5 miles) S35W in Lone Pine canyon where it trends N58W. The official wellhead location is "DOSECC" Federal 2-26, 1144 feet S and 1982 feet E of the NW corner of the NW corner of sec. 26, T3N, R6W, latitude 34°18'52", longitude 117°28'38"W. The site is N 1.3 km (0.8 mile) up the Baldy Mesa road from Cajon Junction at the intersection of I-15 and Route 138. A related older well, "Arkoma" Federal 1-26, is located on the same pad (Silver and James, this volume).

The drill pad is in the Cajon Creek drainage which drains south to the San Bernardino Valley in an incised bedrock canyon across the SAF. This drainage has downcut rapidly, 450 m in the last 700,000 years (Weldon, 1986). To the NW, Cajon Valley forms a broad amphitheater carved into late Cenozoic sedimentary formations. Within 8km of the site highest and lowest elevations are 1700 and 600 m. The recent geomorphic evolution bears directly on interpretations of various experiments at CPDDH.

Regional Geologic Setting

The overall science experiment is focused on the SAF, the most active structure of the transform margin of the North American plate. The drillsite is on the SW edge of the Mojave Desert and at the west end of the San Bernardino Mountains (Figure 1). This range and the San Gabriel Mountains west across the SAF are rising rapidly (1-3 km relief) in apparent response to SAF transpression. Recent studies (Weldon and Sieh, 1985; Meisling and Weldon, in press) indicate a combined right lateral rate of motion on the San Andreas and San Jacinto faults of ~37 mm/year. The rising San Gabriel Mountains have shed broad debris aprons NE across the SAF into the Mojave Desert including the area recently excavated by Cajon Creek.

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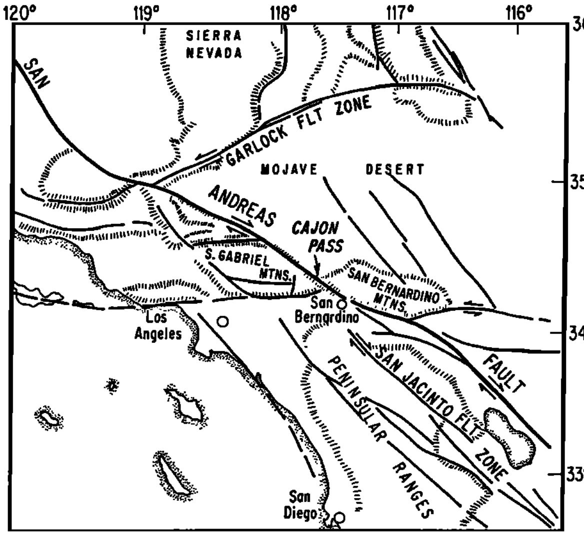

Fig. 1. Location of the Cajon Pass deep drillhole relative to major faults and physiographic features in southern California.

The western Mojave Desert is underlain by Mesozoic batholithic rocks with screens of Paleozoic and early Mesozoic supracrustal rocks. The region has been reduced to low relief, filling shallow Neogene continental basins. Neogene folding of basement contributed to the formation and deformation of the basins (Dibblee, 1967). Continuing folding and faulting are producing prominent basement antiforms along and parallel to the great faults on both margins of the western Mojave Desert. The CPDDH is located on the flank of such an antiform in a Miocene sedimentary basin (Figure 2).

A number of workers (Ehlig, 1968; Silver, 1982) suggested that the western Mojave Desert may be underlain by great low angle faults above distinctive regionally metamorphosed deep-water assemblages of the Rand and Pelona schists. These faults are inferred to be latest Cretaceous to Paleogene, and the schists Mesozoic (?), in age.

The San Bernardino Mountains contain a variety of Mesozoic to Precambrian granitic rocks and remnants of Cordilleran miogeoclinal sedimentary formations. The San Gabriel Mountains are comprised of tectonically stacked Mesozoic granitoids and Precambrian orthogneisses resting on a great mylonite zone above Pelona Schist. This complex tectonostratigraphic assemblage is exposed across the SAF west of the CPDDH in the eastern San Gabriel Mountains (Figure 2).

Recent estimates of total displacement on the SAF system support 310±10 km of right slip (Ross, 1984; Silver and Mattinson, 1986; James, 1986). Plausible correlations suggest that basement terrane displaced from the CPDDH area is found near Shandon and the Red Hills in northeastern San Luis Obispo County (Ross, 1972; Mattinson, 1983).

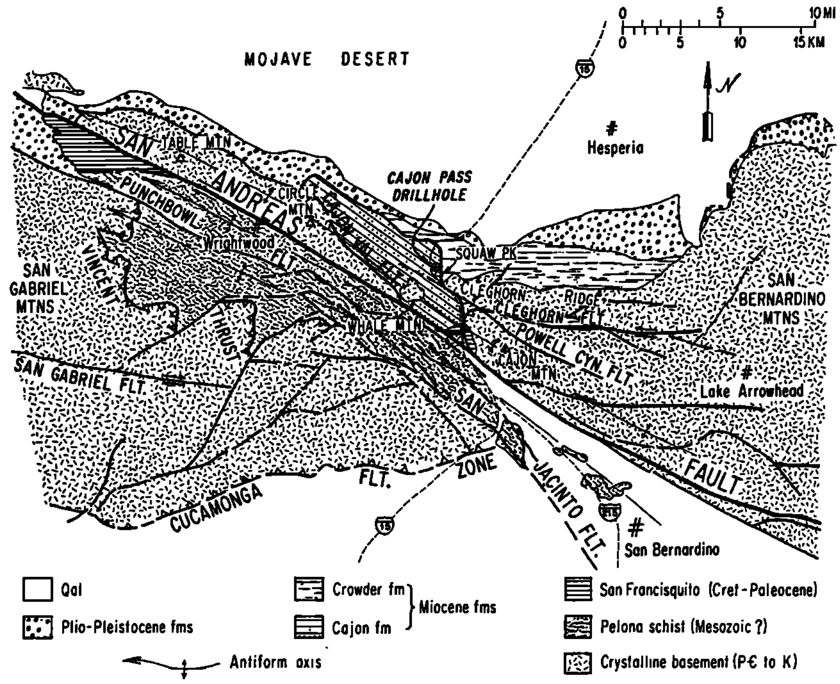

Fig. 2. Generalized geologic map of the Cajon Pass area.

Local Geology

Noble (1954) and Dibblee (1967) provided the basic framework geology for the drillsite. Woodburne and Golz (1972) developed a useable stratigraphy for the Cajon (formerly Punchbowl) Formation. Weldon (1986) refined the geologic mapping, recognized additional important faults and evaluated the late Cenozoic history of the area. Meisling and Weldon (in press) have integrated the site geology into a model for the late Cenozoic tectonics of the NW San Bernardino Mountains. Figure 2 is generalized from these sources.

The local geologic column consists of late Cretaceous(?) to Miocene strata resting on Cretaceous and older basement in which Cretaceous granitoids ranging from sphene-hornblende-biotite granodiorite to biotite granite dominate. They are exposed on Squaw Peak, Whale Mountain and Cleghorn Ridge.

A few hundred feet of marine strata referred to the San Francisquito Formation rest unconformably on basement 5 km S of the drillsite adjacent to the SAF. A marine reptile found in these strata suggests a late Cretaceous(?) age (R. Reynolds, M. Woodburne, pers. comms., 1988). Two km SW on Whale Mountain patches of fossiliferous marine strata up to 168 m thick have been assigned an early Miocene age and referred to the Vaqueros Formation (Woodburne and Golz, 1972). The most widespread outcrops in Cajon Valley are nonmarine sandstones and mudstones variously called "Cajon beds", Punchbowl Formation, or Cajon Formation. We accept the latter. This formation, host to the CPDDH, yielded late middle Miocene to late Miocene vertebrate fossils (Woodburne and Golz, 1972). The Cajon Formation apparently rests unconformably on basement and Vaqueros(?) Formation and by faulting, on San Francisquito(?) Formation. It is faulted against contemporaneous (late-Early to early-Late Miocene) Crowder Formation along the Squaw Peak thrust N and E of the drillsite (Weldon, 1986). Crowder Formation appears to be a separate depositional system resting unconformibly on San Bernardino Mountains basement. Several Pliocene and Pleistocene units, the Phelan Peak deposits, Harold Formation, Shoemaker Gravel, and old alluvium, are fan deposits derived from the San Gabriel Mountains. They once extended across Cajon Valley in a 300+ m blanket.

The area contains significant folds and faults (Figure 2). Immediately NE of the SAF, a line of faulted antiforms extends from Cajon Mountain and Whale Mountain NW through Circle Mountain, and Table Mountain. The pre-middle Pliocene NW-trending Cajon Valley fault separates basement of Circle Mountain on the west from steep NE-dipping Cajon strata. Total displacement is unknown but basal Cajon units contain clasts of the local basement. The Cajon Formation is folded and faulted on W to NW trends with N to NW trending axes predominating in the vicinity of the Squaw Peak fault.

The Cleghorn fault, a major E-W break active in the Quaternary (Meisling and Weldon, in press), separates Cleghorn ridge from Cajon Mountain. It appears to offset the faulted eastern contact of the Cajon Formation along the N-S portion of the older Squaw Peak fault, approximately 3 km in a left-lateral sense. The Cleghorn fault cannot be followed west beyond the alluviated floor of Cajon Valley.

Weldon (1986) identified the NE-dipping Squaw Peak thrust with a N-S vertical tear extending south past Squaw Peak, as a tectonic boundary between the Cajon and Crowder Formations. This fault has been inactive since mid-Pliocene.

Smaller high-angle faults are probably present in the Cajon Formation near the site. Other low-angle faults, not exposed, have been hypothesized by Meisling and Weldon (in press).

The two wells were spudded on a pad in unit 5 (Woodburne and Golz, 1972) of the upper Cajon Formation. The visible local structure consists of steeply dipping (50°-80° NE) strata trending N30°-50°W with minor folds of similar trend.

Methods of Establishing the Geologic Column

The column presented here is an integrated interpretation based on detailed study of drill cuttings and cores. Thirty-four core runs in the first drilling leg yielded 82.3 m of core for 82 percent recovery and 4 percent of well depth. Core diameters ranged from 7.1 to 14.7 cm (2.8 to 5.8 inches); below 707 m most are more than 12.7 cm (5 inches). To construct the geologic column a matrix of parameters descriptive of igneous and metamorphic rock compositions and textures was developed. These were validated by comparing matched cuttings and core. Samples were studied with binocular and

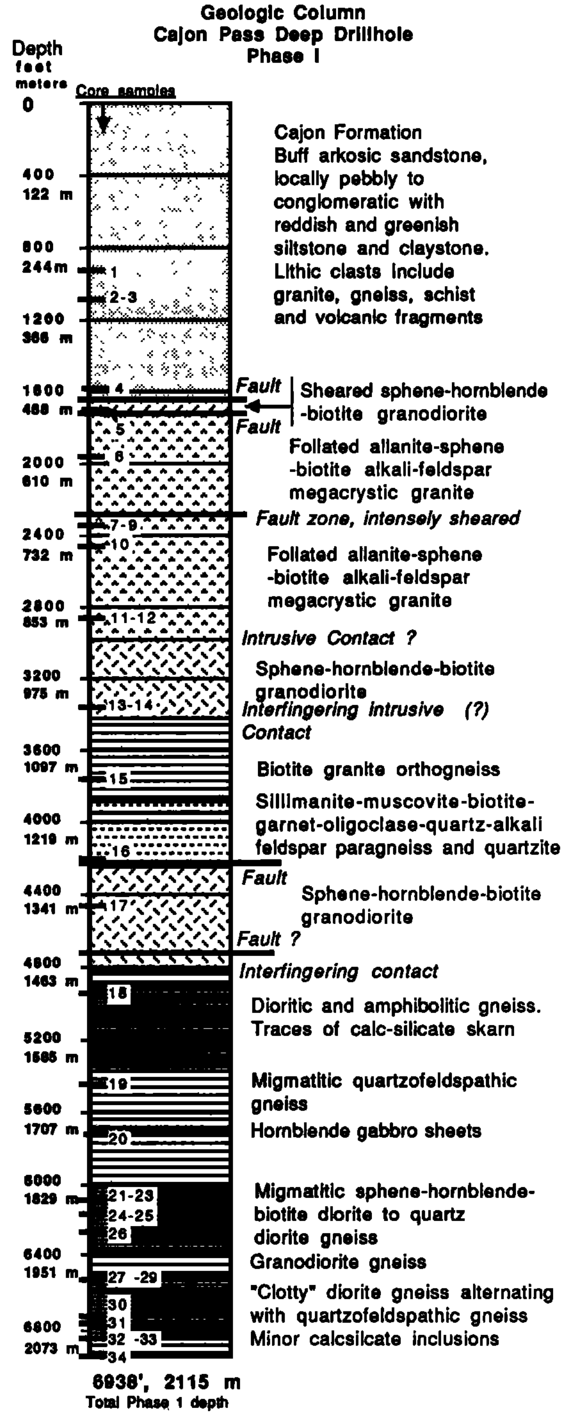

Fig. 3. Geologic column of Phase I of the Cajon Pass Deep Drillhole.

petrographic microscopes; mineral abundances were determined by point counting and visual estimation on thin sections and cuttings. These measurements supersede estimates in excellent graphic logs prepared by the mudlogging contractor. Cores were mapped at scales up to 1:1.

The Cajon Pass Deep Drillhole Column

In drilling phase I, the CPDDH reached 2115 m with a maximum deviation from the vertical of 3.5°. The bottom of the well was 16 m E and 29 m S of the well head. A generalized geologic column is presented in Figure 3.

Starting in the upper Cajon Formation (Unit 5, Woodburne and Golz, 1972), the well penetrated 497 m of buff arkose, minor pebbly arkose and red and green mudstone. Dips are steep to 335 m, and apparently shallower in core 4 (480-483 m). The section is generally characteristic of the Cajon Formation but aspects of core 4 and structural data permit some Vaqueros Formation(?) at the base (see Reynolds and Weldon, this volume).

The first plutonic rock, highly sheared altered sphene-biotite granodiorite, was encountered below a fault at 497 m. In core 5 (521-529 m) networks of thin shears contain chlorite and fine-grained cataclasite. Normal and reverse sense displacements of a few cm are common. Drilling behavior and geophysical logs (Pezard and Luthi, this volume) indicate the bottom contact of this unit is a fault.

At 530 m distinctive foliated allanite-sphene-biotite-alkali-feldspar megacrystic granite was encountered. Cuttings indicate minor alternation with granodiorite. Foliation intensity in the granite increases from core 6 (594-597 m) to core 9 (703-707 m). At 701 m core 7 sampled a cataclastic fault and alteration zone entirely within the granite. Cores 10, 11 and 12 (743-746, 860-860.5, 860.5-861.5 m) are biotite granite converted to augen gneiss with shallow foliations. No local surface equivalents are recognized.

The base of the deformed granite at 917 m is an intrusive contact with younger, weakly foliated sphene-hornblende-biotite granodiorite. This granodiorite is much less deformed than granodiorite in core 5 and resembles surface exposures on Cleghorn ridge and Squaw Peak.

Gneissic intervals appear in the granodiorite at 1045 m and migmatitic granite gneiss, as in core 15 (1138-1141 m), predominates below 1100 m. Below 1189 m muscovite, foxy red biotite, sillimanite and traces of garnet increase and with microcline, oligoclase and quartz dominate at 1250 m. Core 16 (1283-1286 m) sampled this metapelite and interlayered quartzite and entered a fault zone inferred to separate metasedimentary rocks from sphene-hornblende-biotite granodiorite.

This new granodiorite at 1298 m is similar to the two above. In core 17 (1351-1357 m) it is less fractured but is cut by a major alteration zone at 1433 m marked by orange turbid feldspar and chloritized dark minerals. Alteration decreases with depth to a contact of the granodiorite with quartz diorite gneiss at 1469 m.

Between 1469 m and 1631 m bimodal felsic and mafic cuttings represent a layered quartz dioritic gneiss sampled by core 18 (1500-1502 m). Foliated, lineated biotite-hornblende layers alternate with two-feldspar-quartz layers. Near 1631 m cuttings grade to gneisses of granodiorite composition seen in core 19 (1652-1658 m) and the base of core 20 (1741-1744 m). Migmatitic sphene-hornblende-biotite granodiorite gneiss displays low-angle layering and small-scale recumbent folds. Hornblende gabbro appears at 1731 m, 1737 m, and in upper core 20 where it has been brecciated by a felsic intrusion that separates it from underlying gneiss.

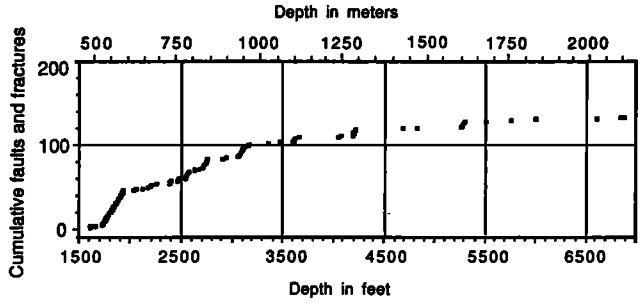

Fig. 4. Cumulative faults and fractures represented by abrupt changes in drilling rate, drilling breaks, as a function of depth in the CPDDH.

Cores 21, 22, 23 (1844-1855 m) include alternations of migmatitic sphene-hornblende-biotite granodiorite and hornblende diorite gneisses and biotite-amphibolite. Cores 24, 25, 26 (1874.5-1876, 1883.7-1884.4, 1902-1906 m) are migmatitic diorite to quartz diorite with minor granite gneiss layers. At 1945 m calcsilicate traces appear. Cores 27, 28, 29 from 1981 m to 1986 m are layered and folded hornblende granodiorite gneisses with inclusions of garnet-diopside skarn, layers of biotite amphibolite, and minor pegmatite.

From 2042 to 2115 m cores and cuttings include biotite-hornblende diorite to quartz diorite gneiss with "clotty" mafic minerals and subordinate fine-grained biotite amphibolite, calcsilicate minerals, and granitic dikes and layers.

Structural Features

All crystalline rocks are foliated, ranging from weak alignment of mafic minerals in the granodiorites to strong preferred orientation of minerals and compositional layering in paragneisses and migmatitic gneisses. Foliation dips are generally low (<30°). Folds in the layered metamorphic rocks are recumbent isoclinal with axes in the foliation.

The well cuts several important brittle faults. Evidence for faults includes abrupt rock contrasts, cataclastic zones and alteration. The faulted sediment-basement contact was marked by increased drill rate and a substantial increase in CO_2. Gamma ray logs indicate a large uranium series anomaly at the contact. A major fault zone from 1286 to 1298 m separates pelitic gneisses and quartzite from granodiorite below. Increased drilling rate marked this fault. Most fault zones are apparent in the geophysical logs (Pezard and Luthi, this volume). Discussion of faulting related to both wells is presented by Silver and James and Pezard *et al.* elsewhere in this volume.

Fractures (and faults) show a systematic decrease in frequency with increasing depth. A plot of cumulative frequency of abrupt changes in rate of penetration, drilling breaks, as a function of depth was prepared with R. Johnson, DOSECC drilling engineer (Figure 4). Observed fracture density in the cores parallels the drilling break frequency. Commonly, fractures in cores contain mixtures of grey comminuted rock, white to pink colored zeolite minerals, calcite and rare pyrite. They are generally steep (60° to 90°) and show little or no offset. Most cores were not oriented during drilling but the strike of fractures has been determined subsequently by downhole logging methods (Pezard and Luthi, this volume). Some fractures run the length of a core. Many fractures show several episodes of dilation and zeolite deposition, reducing fracture permeability of the rocks. A few fractures have zeolite crystal linings that project into open interiors.

Other important systems of fractures contain chlorite and/or, epidote, pyrite, and turbid feldspars. Chlorite-filled fractures are generally less steep and in many cases follow mafic layers in the foliation. Down-dip lineations and centimeter-scale normal and reverse offsets are common. Zeolite mineralization follows or cuts the chlorite-filled fractures in a few samples. The nature of the zeolite mineralization is discussed in James and Silver (this volume).

Summary

The lithologic diversity encountered in the 2.1 km CPDDH is remarkable. It is much greater than was anticipated from nearby surface exposures. There, granodiorite predominates suggesting the CPDDH would penetrate a large pluton. Although structural analyses are still in progress, it appears that faulting, especially low-angle faulting, may have juxtaposed some of the observed lithologies.

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